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UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF WASHINGTON

JOSEPH A. PAKOOTAS, an individual and enrolled member of the Confederated Tribes of the Colville Reservation; and DONALD R. MICHEL, an individual and enrolled member of the Confederated Tribes of the Colville Reservation, and THE CONFEDERATED TRIBES OF THE COLVILLE RESERVATION,

Plaintiffs,

and

STATE OF WASHINGTON,

Plaintiff/Intervenor,

v.

TECK COMINCO METALS, LTD., a Canadian corporation,

Defendant.

NO. CV-04-0256-LRS

WRITTEN DIRECT AND REBUTTAL TESTIMONY OF PLAINTIFFS' EXPERT DR. DIMITRIOS VLASSOPOULOS, PH.D.

I, Dimitri Vlassopoulos, pursuant to 28 U.S.C. § 1746, declare the following:

I make this declaration in connection with my direct testimony in this matter. If called to the witness stand, I would testify as set forth in this declaration.

I. QUALIFICATIONS

1. I am a Principal Scientist with Anchor QEA, LLC, a scientific and engineering consulting firm. Anchor QEA is a multi-disciplinary environmental, science, and engineering consulting firm with 22 offices in the United States. Anchor QEA has been engaged jointly by the State of Washington and the Confederated Tribes of the Colville Reservation in connection with this matter.

2. I hold a B.Sc. degree in Geology from Concordia University (1986), an M.Sc. degree in Geological Sciences from McGill University (1989), an M.S. degree in Geochemistry from the California Institute of Technology (1993), and a Ph.D. in Environmental Sciences from the University of Virginia (2000). I have more than 20 years of experience conducting and directing scientific investigations in the United States and Canada. I have extensive experience investigating environmental contamination from industrial sources including mining and metallurgy. I have edited a book, authored or co-authored approximately 20 scientific articles, and published numerous abstracts, pertaining to various aspects of environmental geochemistry, environmental forensics, fate and transport of contaminants, and remediation, among other topics.

3. A copy of my curriculum vitae is attached as **Exhibit 1**.

II. EXPLANATION OF TASKS

4. I was tasked with investigating whether slag and other wastes generated at Teck Cominco's (Teck) Trail Operations and historically discharged into the Columbia River in Canada have come to be deposited within and resulted in contamination of the sediments of the Upper Columbia River (UCR) and Lake

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Roosevelt in the United States. I was also asked to evaluate and develop opinions as to whether the contamination due to Teck's discharges continues to release hazardous substances to the aquatic environment.

III. SUMMARY OF OPINIONS

5. My primary opinions as they relate to Teck's liability in this matter are summarized in this Part. The supporting factual and scientific bases for my stated opinions are discussed in greater detail in Part VI.

6. **Opinion 1**: Slag and sewer effluent discharged from Teck's Trail Operations directly into the Columbia River have been transported by the River into the United States, where they have accumulated within and contaminated the sediments of the Upper Columbia River and Lake Roosevelt, between the U.S. – Canada border and the Grand Coulee Dam.

7. **Opinion 2**: Slag discharged from the Teck smelter is a predominantly glassy material. Once released into the aquatic environment, it slowly but irreversibly breaks down to more stable weathering products by physical and chemical processes. Through the action of these processes, hazardous substances present in the slag including arsenic, antimony, barium, cadmium, copper, lead, and zinc are released over time from the slag to the sediment porewater and the aquatic environment of the (UCR) and Lake Roosevelt.

8. **Opinion 3**: Metals contained in sewer effluents are discharged from the Trail smelter (including arsenic, cadmium, copper, mercury, lead, and zinc) in both dissolved and particulate forms. Such metals partition to particles in the river in a dynamic process that results in continual exchange of metals within the river environment. Metals partitioned to particles are deposited with particles to river sediments in the UCR and Lake Roosevelt. Particulate-bound metals are carried downriver and eventually settle out of the water column as fine-grained sediment

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in depositional areas in the UCR.

9. **Opinion 4**: Metals present in the sediments of the Upper Columbia River represent continuing, long-term sources of potentially toxic metal contaminants. Slag weathering processes and subsurface sediment biogeochemical processes drive the re-release of metals stored in the contaminated sediments, facilitating their remobilization and transfer to sediment porewater and the aquatic environment.

IV. METHODOLOGY

10. In developing my opinions, I undertook a series of studies and investigations which included the following:

a. I comprehensively reviewed information about the discharges of hazardous substances from Teck's Trail facility to the UCR, including the chemical composition and quantification of discharges. My review extended to primary documents such as the Upper Columbia River Phase I Sediment Sampling Data Evaluation (USEPA 2006) and the Kootenay Air and Water Quality Study (BCMoE 1977) and the expert report of Dr. Paul Queneau (2010; updated 2011).

b. I reviewed documents and other information on the chemical composition of discharges from the Trail facility.

c. I reviewed documents and other information on the physical nature of the discharges. For example, since the 1930s, Teck slag has been fumed and consists of predominately sand sized, glassy iron-rich granules, while Trail sewer effluents carry metals in both particulate and dissolved forms.

d. I reviewed relevant scientific literature regarding the geochemical characteristics and environmental behavior of slag and other types of glasses (natural and artificial).

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e. I reviewed relevant scientific literature on the environmental behavior of the metals contained in Teck's sewer effluent discharges, including material documenting the accepted processes known to control the transport and deposition of metals in river systems.

f. I evaluated the physical and chemical conditions of the river and information on the transport potential of the river, including but not limited to work done by Plaintiffs' experts Dr. David McLean and Dr. Victor Bierman to confirm the river's potential to transport and deposit slag and sediment particles.

g. I compiled, reviewed and analyzed an extensive sediment chemistry database prepared for the Site containing the results from investigations and studies undertaken by government agencies including the United States Environmental Protection Agency (EPA) and the United States Geological Survey (USGS), plus the results of new sampling conducted at the Site to support my evaluation and the evaluation of Plaintiffs' other experts. This database includes sediment samples from locations within the Columbia River as well as from tributary sources.

h. Utilizing this extensive sediment sampling database, I performed multivariate statistical analysis including principal components analysis and factor analysis (PCA and FA), which allowed me to identify the strongest geochemical signatures present in UCR sediments and map their distribution within the Site, in order to trace these signatures back to their points of input to the system.

i. I compared lead isotope ratios of whole sediment and slag particles taken from the sediment cores with lead isotope ratios of the principal ores processed at the Trail smelter. This allowed me to unequivocally

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authenticate that the slag particles found in the UCR originated at the Trail smelter.

j. I reviewed numerous historical and published studies of Teck slag as well as other slags that document the leaching of metals from slag. This review included both Teck's own studies and studies conducted by others.

k. I reviewed work done by the USGS on conditions in the UCR, including studies of releases of metals from UCR sediments.

l. I directed a 2010 sediment coring and sampling study (2010 Coring Study) in the UCR focusing on locations upstream of Northport, Washington (downstream of Trail but upstream of the former LeRoi smelter that ceased operating in the early 1920s) and on locations upstream of the reservoir. I selected the general locations to be sampled within the UCR, directing sampling just downstream of the International boundary, at Black Sand Beach, at Deadman's Eddy, at Onion Creek, and at China Bend. These cores were sampled for chemical composition, and the extensive data produced were included in the sediment chemistry database prepared for the Site and mentioned above. I later directed sampling from these cores for use in leaching studies and lead isotope ratio testing.

m. I commissioned Professor Joseph Ryan of the University of Colorado at Boulder to conduct laboratory slag leaching experiments, using Teck slag particles taken from the 2010 Coring Study UCR sediment cores, to document the release of metals from slag when it is immersed in Columbia River water.

n. I collected and analyzed samples of porewater from slag-rich locations within the UCR to directly document the release of metals from slag under in situ conditions in the river. The porewater sampling locations included the

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same locations as the sediment cores from the 2010 Coring Study selected for Professor Ryan's leaching studies.

11. The results of my work, and the opinions that I reached, are provided in detail below. This declaration addresses both my primary and my rebuttal opinions. The rebuttal opinions are incorporated into the discussion of my opinions and work in Part VI of the declaration, and supplemental rebuttal points are also made in Part VII.

V. INTRODUCTION TO OPINIONS

A. Metallurgical Slag Historically Discharged to the Columbia River by Teck at its Trail, B.C. Smelter (Teck Slag) Has Accumulated in Sediments of the Upper Columbia River in the United States (UCR or UCR Site). Slag Particles Visible in the River Can Positively Be Identified as Teck Slag, Especially Upstream Of Northport Where No Other Source of Slag Has Been Identified.

12. Slag particles are visible in the Columbia River, and can be distinguished from sediment by their black color, glassy luster, and jagged edges. The fact that slag can be distinguished from sediment in general, or that Trail smelter slag in particular has come to be located at the UCR Site (also, "Site," defined as the geographic extent of the UCR, including Lake Roosevelt, where hazardous substances have come to be located), has not been disputed by Teck's experts, particularly in the reach upstream of Northport. Anticipating the need to prove otherwise, I had nonetheless undertaken to fingerprint slag particles found in site sediments upstream of Northport.

13. I fingerprinted the slag from the river in two independent ways: lead isotope and geochemical fingerprinting. Through lead isotope testing, I confirmed this to be Teck slag by matching the lead isotopes in the slag to the unique isotopic signature of the lead ores processed at Teck's Trail smelter. I also analyzed the extensive sediment sampling results taken by the EPA and others at the UCR Site,

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and not only found an identifiable geochemical signature in contamination at the Site directly attributable to Teck slag, but found this to be the dominant signature recorded in sediments for a significant distance downstream of Trail and into the United States. Both methods independently confirmed that the slag particles found upstream of Northport originated from Teck.

B. Teck Slag Leaches Metals to the Environment at the UCR Site.

14. Teck slag is inherently unstable. It slowly but irreversibly breaks down in the river environment by physical and chemical processes, and thereby leaches heavy metals and metalloids including arsenic, antimony, barium, cadmium, copper, lead, and zinc to the sediment porewater and the aquatic environment in the Columbia River.

15. Microscope images of Teck slag taken from the river show that this breakdown is occurring: An outer weathered layer is visible on Teck slag particles that is indicative of weathering and leaching. The images clearly show the discontinuous, cracked, and peeling nature of this outer layer—indicating it is continuously removed from the slag particles by weathering processes including abrasion in the river, and that fresh slag surfaces are continually exposed to dissolution. This process is evidence of leaching.

16. Numerous past studies performed by Teck, by the Canadian federal government, and by the USGS placed Teck slag into or in contact with water to study its propensity to leach. All of these studies showed that slag leached under the conditions tested. In addition, I directed my own leaching studies in which Teck slag sampled from the river upstream of Northport was tested for leaching into Columbia River water also sampled from the Site. The result was unequivocal: Teck slag leached metals under every representative river condition tested.

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17. None of Teck's defense experts tested whether Teck slag leaches. A single Teck defense expert, Dr. Arthur Sandy Riese (Riese), theorized that Teck slag would not leach after microscope examination of a sample of slag particles sampled from a location upstream of the International boundary. The technique did not establish whether metals leaching occurred from the slag particles.

18. In the same slag dominated areas upstream of Northport from which the Teck slag samples were sampled, I conducted a porewater study and confirmed the release of these same metals to the sediment porewater (interstitial water in sediment). In rebuttal, I further confirmed the release to porewater came from Teck's waste, by lead isotope testing of the porewater and showing it has the same unique signature found in the ore processed at Trail.

19. I concluded that Teck slag has leached and continues to leach at least the following metals and metalloids into and from the sediment and aquatic environment of the UCR Site: aluminum, antimony, arsenic, barium, cadmium, cobalt, copper, lead, manganese, selenium, and zinc.

C. Metals Discharged in Teck's Sewer Effluent, Historically in Great Quantities, Have Also Deposited to Sediment at the Upper Columbia River Site.

20. Site data confirms that the deposition of metals from Teck's sewer effluent has occurred. The metals in Teck's sewer effluents (including arsenic, cadmium, copper, mercury, lead, and zinc) were discharged in both dissolved and particulate forms. Particulate-bound metals would have been carried downriver and eventually settled out of the water column with fine-grained sediment in depositional areas known to exist in the UCR Site. In addition, dissolved metals have an affinity to partition to sediment particles, so a portion of the dissolved metals load released to the river system would also have adsorbed onto suspended

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particulate matter, have been carried downriver, and eventually deposited with sediment.

21. Geochemical fingerprinting revealed a separate signature for Teck effluent that is recorded in the sediment contamination throughout the Site. Though other sources could have contributed to this signature or to contamination in general from tributaries downstream of Teck's facility, no other source explains the fact that these signatures are first seen in the sediments at Teck's Trail facility and then continue downstream, into the United States.

22. I concluded that metals including arsenic, cadmium, copper, mercury, lead, and zinc have partitioned to, deposited in, released from, and contaminated the sediment and aquatic environment of the UCR Site.

D. Metals in sediment will continue to release due to biogeochemical processes ongoing in the Columbia River

23. The Columbia River is a dynamic environment. Once metals are deposited or are otherwise released to sediment, remobilization of metals and their re-release into sediment porewater and the aquatic environment results from natural biogeochemical processes. The rate and extent of metals release is a function of conditions within the sediments, which are expected to vary across the Upper Columbia River site, depending in part on factors such as sediment grain size, organic matter content, metal concentrations, and burial depth. These processes occur to some extent, and at various locations, throughout the Columbia River, as they do in all major river systems.

24. The smelter slag and sewer effluent-related metals present in the sediments of the Upper Columbia River thus represent continuing, long-term sources of potentially toxic metal contaminants to the UCR environment. Slag weathering processes and subsurface sediment biogeochemical processes drive the

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release of metals stored in the contaminated sediments, facilitating their transfer to the aquatic environment, and ultimately leading to environmental exposure.

VI. OPINIONS

A. Trail Smelter Slag and Sewer Effluent Metals Are Found at the UCR Site.

1. Characteristics of Teck Slag Discharged from the Trail Smelter

a. Granulation and elevated metals composition of Teck slag

25. The Teck smelter located at Trail, British Columbia, has been in operation since 1896. Since at least 1930, and as early as 1920, water-granulated slag, a by-product generated from the lead smelting operations, was discharged to the Columbia River. Figures 1, 2, and 3 are microscope images of Teck slag. Additional images of slag are attached as **Exhibit 2** and show the physical variation in Teck slag particles.

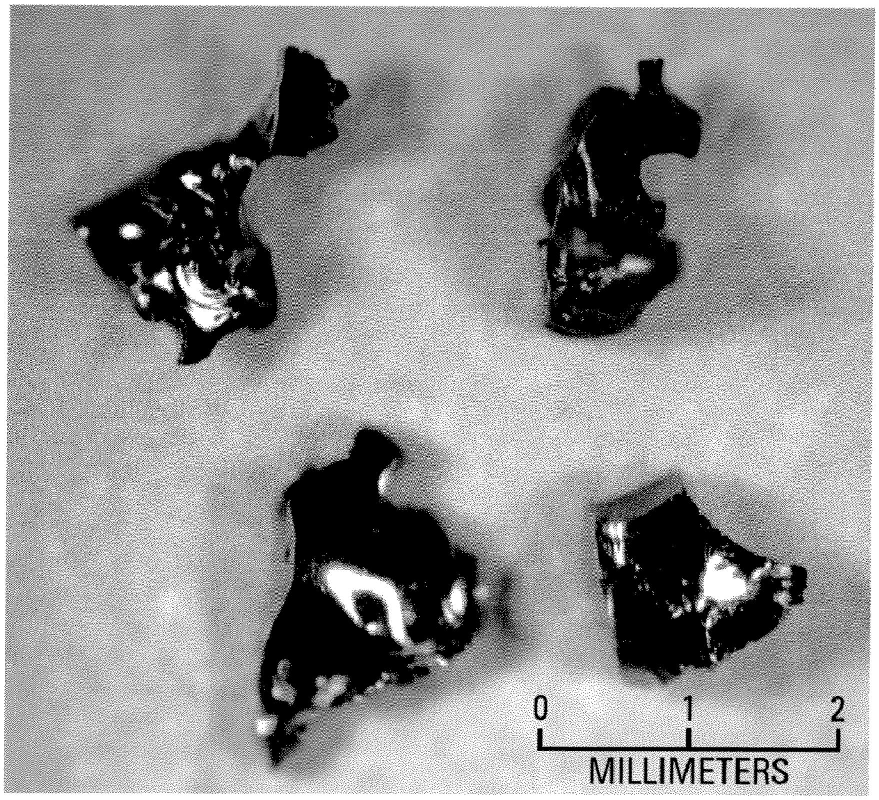

Figure 1. Photomicrograph of Teck slag grains collected near Black Sand Beach (River Mile 743) [USGS 2005].

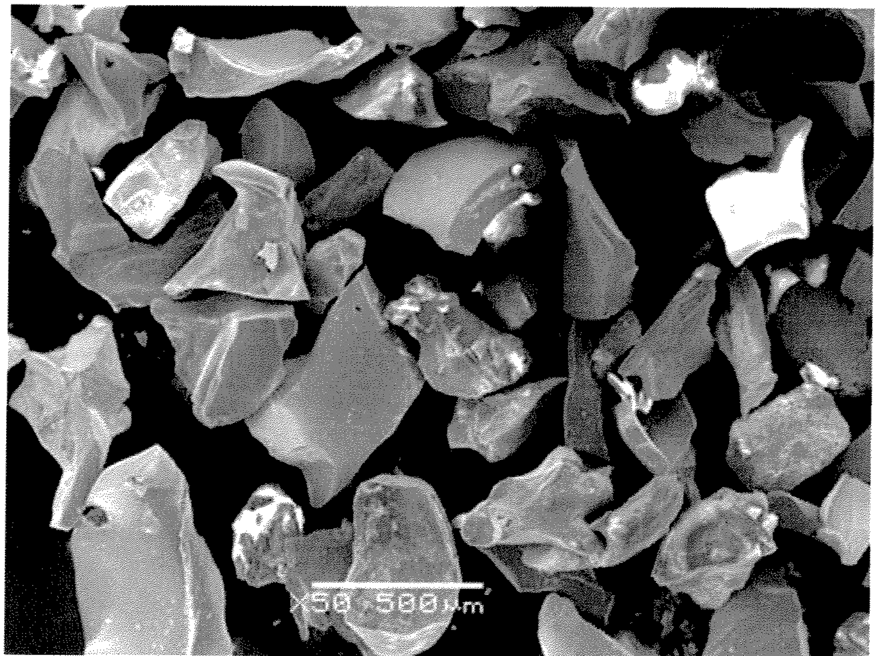

Figure 2. Scanning electron microscope (SEM) image of Teck slag grains isolated from UCR sediment collected near the International Border (River Mile 745). Scale bar is 0.5 mm. [Ryan and Mohanty 2011]

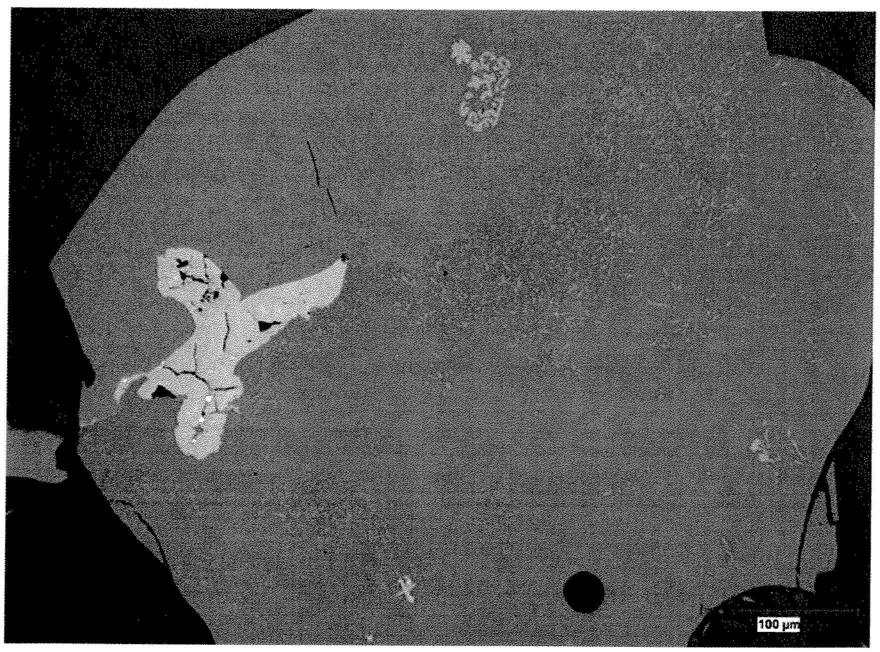

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Figure 3. Photomicrograph of Teck slag grain from Trail showing a copper-rich inclusion (bright area). Scale bar is 0.1 mm [Hazen 2010b].

26. Teck's practice of discharge directly into the river continued until 1995 when slag river disposal was eventually discontinued. Over this period of time, it is estimated that on the order of 10 million tons of granulated slag were produced and ultimately discharged to the Columbia River (USEPA 2006; Queneau 2011). Teck does not dispute that it discharged at least 9.97 million tons of slag into the Columbia River (Higginson 2011).

27. Granulated slag that was discharged directly to the Columbia River is the primary solid-phase byproduct of the smelting furnaces at Trail. Slag from lead smelting is granulated using water to result in a relatively uniform grain size, which facilitates transport of the byproduct. Since the 1930s, granulated slag has also been fumed. Fuming is a process whereby molten slag is exposed to a reducing (low oxygen) atmosphere which promotes the volatilization of zinc from the slag which can then be recovered. In addition to recovering a portion of the zinc, the fuming process also recovers additional lead.

28. The granulated, fumed slag consists predominantly of sand-sized, glassy iron-rich granules that contain various amounts of residual metals. Previous studies conducted by Teck and others provide information on the bulk chemistry, grain size distribution, and physical properties of Trail smelter slag. The bulk chemical composition of water-granulated, fumed slag consists of iron (31.5 to 49.1 percent by weight as Fe_2O_3), silica (21.5 to 29.4 percent as SiO_2), and calcium (9 to 17 percent as CaO). In addition, the ranges of metals concentrations shown in Table 1 have been compiled from analyses of bulk samples (CH2M Hill 2004b; Queneau 2011; Hazen 2010b).

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Table 1
Reported Metals Concentrations in Trail Smelter Slag

Metal	Concentration
Antimony	<25 (below detection limits) to 326 milligrams per kilogram (mg/kg)
Arsenic	13 to 265 mg/kg
Barium	39.7 to 2,100 mg/kg
Cadmium	0.67 to 300 mg/kg
Chromium	210 to 1,370 mg/kg
Cobalt	37.6 to 344 mg/kg
Copper	1,800 to 11,900 mg/kg
Iron	279,000 to 339,000 mg/kg
Lead	14 to 6,650 mg/kg
Manganese	5,330 to 11,500 mg/kg
Mercury	<0.005 mg/kg (below detection limits) to 0.02 mg/kg
Nickel	17.2 to 41.1 mg/kg
Selenium	0.57 to 0.77 mg/kg
Vanadium	36 to 85 mg/kg
Zinc	15,300 to 48,200 mg/kg

29. The physical appearance of slag, as shown in the figures above, is very distinctive. Slag particles can vary in size – especially due to weathering processes, which are discussed further below. They are visible in sediments at the UCR Site, and can be visually distinguished from non-slag sediment by their black color, glassy luster, and jagged edges (Figure 4).

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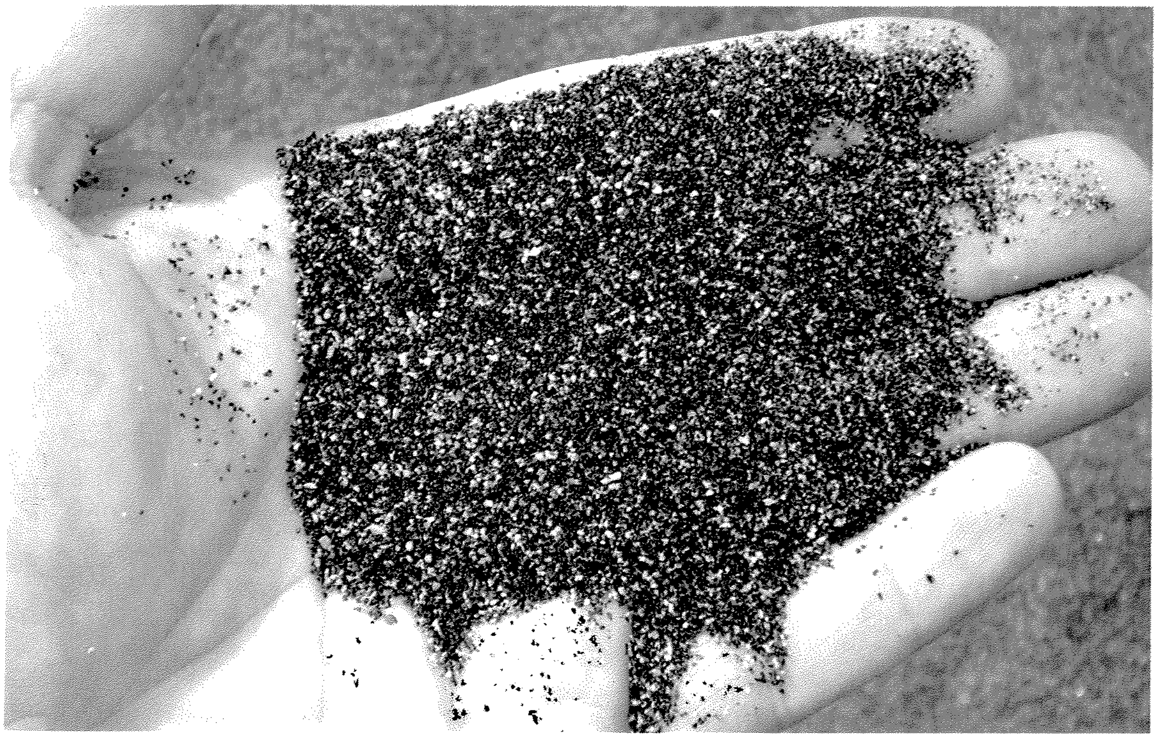

Figure 4. Abundant Teck slag grains (black) visible in sediment at Black Sand Beach.

30. The chemical composition of slag is also very distinctive. When compared to the typical ranges of element concentrations in natural soils and sediments compiled in the literature (San Juan 1994; Mason and Dragun 1996; Reimann and de Caritat 1998), it is evident that slag is highly enriched in iron, zinc, copper, and manganese. Metallurgical slags, like Teck slag, are commonly referred to as "iron-rich" distinguishing them from other forms of glasses which are not enriched in iron. Enrichment in antimony, arsenic, barium, cadmium, chromium, cobalt, and lead may also be significant. Table 2 summarizes the total masses of metals discharged in Teck's slag over the period of discharge (Queneau 2011).

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Table 2
Total Masses of Metals in Teck Slag Discharged to the Columbia River

Metal	Mass Discharged 1920-1997 (Tons)
Arsenic	2,090
Cadmium	130
Copper	29,000
Lead	14,800
Mercury	nil
Zinc	389,900

b. Teck slag continuously weathers in the river environment.

31. Teck slag, being predominantly glassy in nature, is susceptible to loss of mass due to physical and chemical weathering (Bril et al 2008; Ettler et al 2001, 2009; Lottermoser 2002; Parsons et al 2001). Due to the iron-rich nature of slag glasses, such as Teck slag, the most obvious and visible sign of slag weathering is the development of a surface layer of hydrous iron oxide or "rust". Such weathered layers have been observed on the surfaces of slag particles recovered from various locations within the Columbia River downstream of Trail, both in Canada (e.g. Fort Shepherd, Hazen 2010a) and within the UCR Site, including locations upstream of the site of the former LeRoi/Northport smelter (USGS 2005, Hazen 2010b, Nelson 2011). In contrast, slag particles analyzed by Teck which were not exposed to the river environment do not exhibit a weathered surface layer (Hazen 2010b).

32. The weathered surface layer of slag particles is readily observed under a microscope. **Exhibit 2** presents a selection of photomicrographs and scanning electron microscope (SEM) images of slag particles from various UCR slag studies. As is evident in these images, the weathered surface layer is invariably quite thin (generally only a fraction of a millimeter in thickness), cracked, and

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discontinuous, and appears to easily become detached from the slag particles exposing the underlying fresh slag surface. Figure 5, in particular, shows a Teck slag particle with an extensively pitted slag surface underneath the outer weathered rim, indicating dissolution. The formation of the rim is not dissimilar to the oxidation described in the preceding paragraph. The other images and photographs in **Exhibit 2** also show the tendency of the weathered rims to separate from the slag interior. They also indicate surface precipitate formation on slag, likely resulting from oxidation of iron leached from the slag particles.

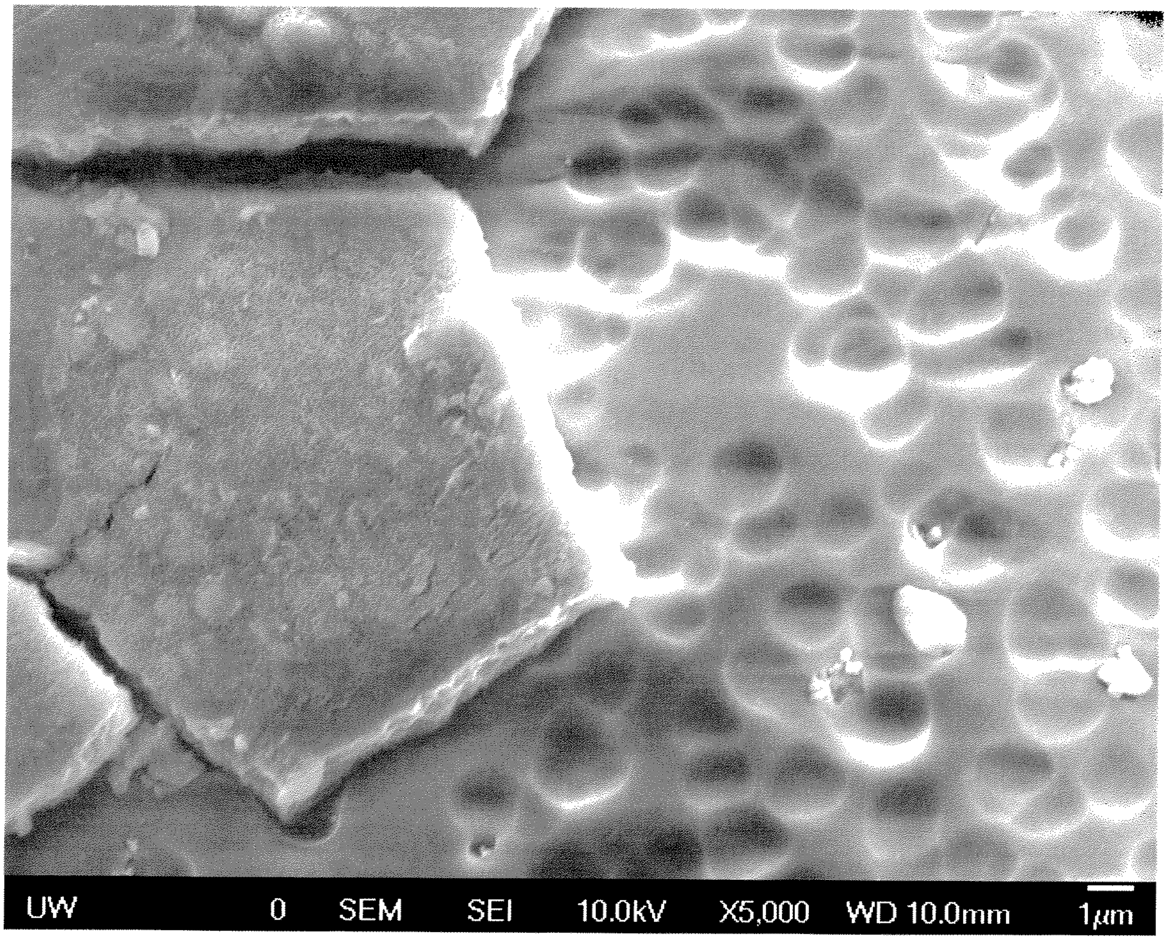

Figure 5. SEM Image of slag grain surface showing cracked and peeling outer weathered layer and pitted slag surface underneath.

33. The process of rim formation and detachment continuously exposes

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fresh slag surfaces to the river environment. And, as they become detached, the outer slag layers are then subject to resuspension and further transport in the river system, as evidenced by studies documenting downstream fining of riverbed sediments (Johnson et al. 1990; CH2M Hill 2006; McLean 2011).

c. As a glassy material, Teck slag is subject to the progressive leaching of its constituent metals into the river environment.

34. Glasses, whether natural or synthetic, are metastable materials. This means that in the environment, they slowly, spontaneously, and irreversibly break down over time to produce more stable weathering products (White, 1984). A large body of scientific literature documents the leaching of metals from both natural and synthetic glasses (White 1984; Gislason and Oelkers 2001, 2003; Perret et al 2003; Wolff-Boenisch et al 2004a,b; Hausrath et al 2009).

35. The glassy nature of Teck slag is a key defining characteristic that determines its propensity to leach chemical constituents into the aquatic environment. In water environments, the weathering of glass proceeds by dissolution and leaching of constituents from the matrix, and slags have been repeatedly shown in numerous studies to leach metals to water (Ettler et al 2004; Lastra et al 1998; Nener 1992; Parsons et al 2001; Piatak et al 2004; Piatak and Seal 2010; Seignez et al 2006, 2007, 2008). Certain metals are also released from weathering of metal sulfide inclusions in the slag. These inclusions are very reactive and are readily oxidized and release dissolved metals when exposed to oxygen in the water. Acid mine drainage is a familiar example of the result of weathering of sulfides. Weathering continually exposes fresh surface area on slag particles as the particles break down.

36. According to reports on the composition and mineralogy of Canadian smelter slags conducted by the Canada Centre for Mineral and Energy Technology

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(CANMET 1995; Lastra et al 1998), Teck slag is composed almost entirely of an iron-rich, amorphous glass. Metal-rich inclusions containing copper and antimony (with traces of iron, nickel, and arsenic) and copper-iron sulfide also occur within the glass matrix. Essentially all of the zinc (3.4 percent by weight) in the slag occurs in the glass phase. Similar findings were also reported in a later study by Microlab Northwest (2001). In addition to the copper-antimony and iron copper sulfide phases, this study also identified a separate lead-rich phase. More recently, Teck has reported on the characteristics of archived Trail smelter slag samples from the early 1990s (Hazen 2010b). Their results are generally consistent with the findings of the previous studies and show that the slag consists largely of amorphous glassy particles with variable but generally lesser amounts of copper-rich sulfide inclusions and iron oxide crystals.

37. All of these studies support a conclusion that Teck slag consists mainly of an iron-calcium-silicate glass matrix with metallic and sulfide inclusions. Most of the zinc content is found in the glass, while copper, antimony, and arsenic tend to be concentrated within the metal/sulfide inclusions. Iron, which is the most abundant metal in slag, is also relatively insoluble under normal surface water conditions. As iron is leached out of the glass, it forms precipitates of hydrous ferric iron oxide which coat the slag particles. The hydrous iron oxide is a separate phase and not merely altered glass, and has an affinity to take up other metals, which are also leached from the slag. A portion of the metals leached from slag will be retained in the iron oxide coatings while the remainder is leached into the surrounding water.

38. These observations offer compelling evidence that slag, once released to the UCR, dissolves and leaches metals and its other component materials seeking more stable secondary phases such as hydrous iron oxide. This is a

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ubiquitous and continuous process that results in the progressive dissolution, alteration, and ultimately disintegration, of the slag particles over time. Not a single study known to me has ever concluded that slag does not leach when placed in contact with water. The rate of this progressive leaching of individual metals from slag deposited in the river environment will vary as a function of the metal, its concentration in slag, and the local environmental conditions which vary across the UCR site.

d. Contrary to Riese's unproved theory, the weathering rim formed on Teck slag is evidence of leaching.

39. Riese suggested that the iron oxide layer found on slag grains forms a Passivating Reactive Interphase (PRI) which prevents leaching. The concept of the PRI has its origins in the nuclear waste disposal field where it has been proposed to explain the leaching and alteration of borosilicate glasses used for nuclear waste applications (Frugier et al 2008). Even within that research community, the existence of the PRI is still debated and not universally accepted.

40. Moreover, the borosilicate glasses in which the PRI theory is discussed are unlike any slag glasses or natural glasses in that they contain very little or no iron, and high levels of boron (15-20% B_2O_3) and sodium (10-15% Na_2O). Some also contain high levels of zirconium and lithium. The concept and studies on which the PRI theory is based suggest nothing about the dissolution behavior of iron-rich silicate glasses such as Teck slag and the formation and behavior of hydrous iron oxide weathering rims.

41. The PRI concept, as put forth for borosilicate glasses, does not provide insight into the chemical or environmental behavior of Teck slag, but the extensive literature on the leaching of iron-rich slag glasses yields much more useful insight into the alteration of Teck's iron-rich slags. (Ettler et al 2004; Lastra

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et al 1998; Nener 1992; Parsons et al 2001; Piatak et al 2004; Piatak and Seal 2010; Seignez et al 2006, 2008) The diagram below plots the concentrations of the major elements silicon and iron for a variety of glasses that have been studied in the literature (Figure 6). (Ettler et al 2003; Hazen 2010b; Ryan and Mohanty 2011; Crovisier et al 1992; Techer et al 2001; Rajmohan et al 2010) This diagram shows that nuclear waste (borosilicate) glasses are extremely different in composition from slag glasses, basaltic glasses are intermediate, and slag glasses have a range of compositions at different sites, but are much closer in composition to one another than to different types of glasses.

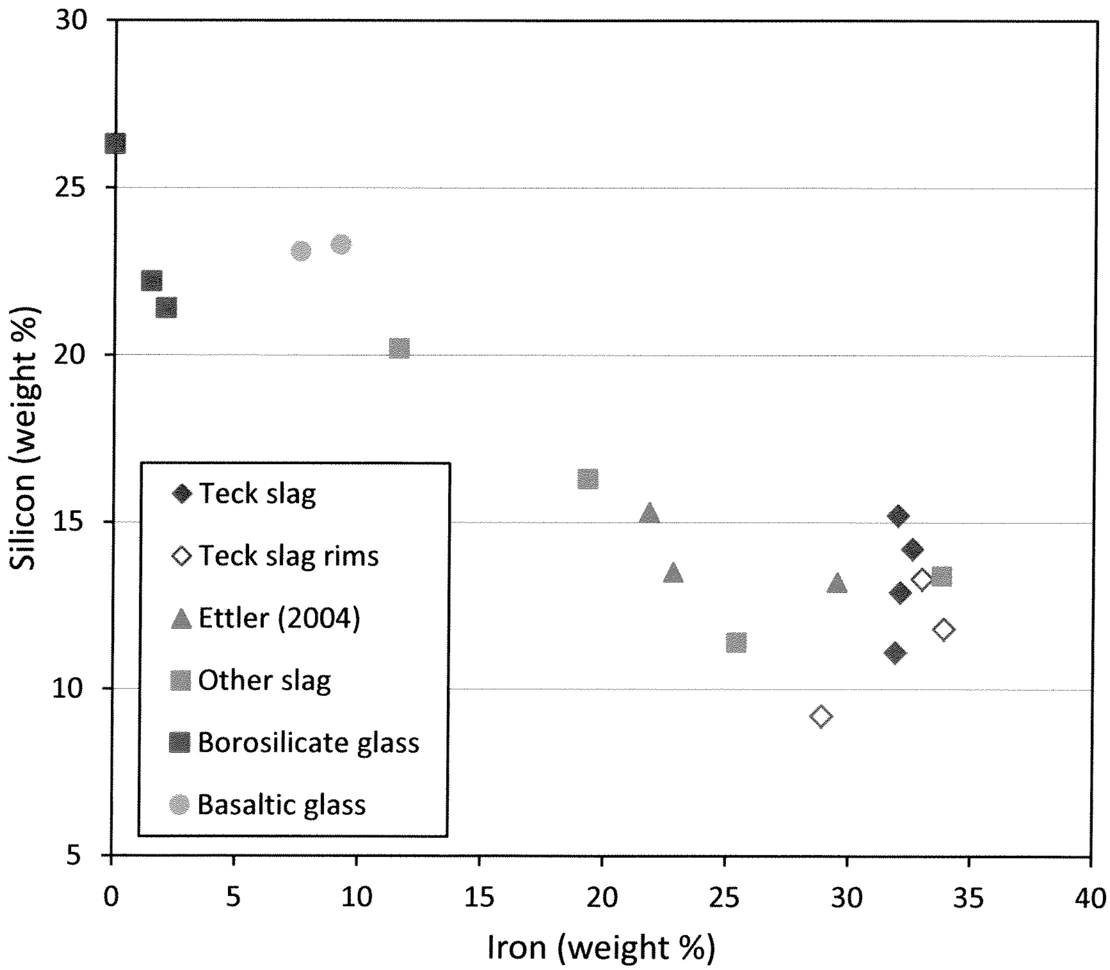

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Figure 6. Concentration of silicon and iron in a variety of natural and artificial glasses.

42. In sum, Riese's PRI theory has no application to Teck's slag, which as an iron-rich glass has different dissolution and weathering characteristics than borosilicate glasses. As discussed below, Riese undertook no studies to disprove that Teck slag leaches its constituent metals and that its outer weathered layer is evidence of leaching.

2. Characteristics of Teck Sewer Effluents

a. Overview of Teck sewer effluent composition and volume

43. Historically, non-slag waste effluent from the Trail facility has been discharged to the Columbia River through several sewer outfalls including the fertilizer operation, the metallurgical plants, and the slag launder system (Queneau 2011). These sewers historically discharged significant quantities of metals to the river. For example, between 1980 and 1996, average discharges for dissolved metals were as high as 18 kilograms per day (kg/d) of arsenic, 62 kg/d of cadmium, 200 kg/d of lead, and 7,400 kg/d of zinc (Cominco 1997b). Total metals discharges were generally higher than these estimates, however, because a significant portion of the metals are discharged as solid particulates. Additionally, up to 4 kg/d of total mercury and 350 kg/d of dissolved zinc were discharged from fertilizer plant operations (Cominco 1997b).

44. Queneau (2010; updated 2011) estimated the cumulative non-slag metals discharges (i.e., effluents) to the Columbia River from the Trail facility between 1923 and 2005. These estimates are reproduced in Table 3. A comparison of the total mass discharges of slag-associated metals for approximately the same time period (Table 2) shows that about as much lead and twice as much zinc was discharged to the Columbia River in the form of slag as

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was discharged in the form of effluents, while most of the cadmium and essentially all of the mercury have been discharged via sewer effluents. These estimates do not include additional discharges of metals to the river from the numerous reported accidental spills and permit exceedances that have occurred at the facility (MacDonald 1997), and that continue to occur (Duncan 2008a, 2008b).

Table 3[1]

Total Masses of Teck Effluent Metals Discharged to the Columbia River

Metal	Mass Discharged 1923-2005 (tons)
Arsenic	376
Cadmium	1,790
Lead	14,800
Mercury	223
Zinc	177,000

b. Metals in Teck sewer effluents were discharged in dissolved, colloidal, and particulate form, subjecting those metals to sorption and settling (for the dissolved and colloidal phase discharges) and settling (for the particulate phase discharges) within the UCR

45. In this section, I discuss the chemical properties of Teck's sewer effluent. The chemical properties of the effluent determines its expected behavior within the complex Upper Columbia River system which transitions from a fast-flowing river to a lacustrine reservoir with periodic drawdowns within the 150-mile reach of the UCR Site.

46. Both dissolved and particulate metals have been discharged to the Columbia River from Teck's sewer effluents and accidental spills. For example,

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[1] Teck defense expert Higginson does not dispute that these metals were discharged into the river as sewer effluent, although he has not agreed to the masses of discharge.

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data contained in Teck's 1997 Effluent Management Plan (Cominco 1997b), and relied on by Queneau (2010, 2011), indicates that most of the lead, zinc, mercury and copper, and significant portions of the cadmium and arsenic discharged via the sewers was in particulate form. These metals discharged from Teck's sewer effluents, including arsenic, cadmium, copper, lead, mercury, and zinc have a strong affinity to attach to surfaces of suspended particulate matter, especially iron oxides (Hart 1982; Gaillardet et al. 2003). This process, called adsorption, regulates the partitioning of the metals between dissolved and particulate forms in aquatic systems (Stumm and Morgan 1996; Stumm 1992).

47. Adsorption of metal cations, including cadmium, copper, lead, zinc, and mercury, onto sediment particle surfaces is favored by the neutral to slightly alkaline pH of the river water (Stumm 1992); therefore, a significant portion of the metals load is expected to be partitioned to suspended particles and carried in particulate form within the river environment.

(1) Evidence of partitioning of metals in Teck's sewer effluents between dissolved and particulate form

48. To gain further understanding of the state of metals from Teck's sewer effluents near their point entry into the UCR Site, as part of my rebuttal to Riese, I looked for direct evidence of their phase distribution. I did this by comparing metals concentrations in filtered (dissolved) and unfiltered (total) water samples collected from the same location (just upstream of the International boundary) at the same time. The difference between total and dissolved concentrations represents metals associated with particles that are removed by filtering the sample, and therefore provides an estimate of the particulate metals concentration in a sample.

49. In Figures 6 to 9 below, I present data for water samples collected

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from the Columbia River at Waneta, B.C., near the International Border (from a spreadsheet named "Waneta Surface Water Quality_Graph Data.xlsx," produced by Teck). These figures plot total versus dissolved concentrations for cadmium, copper, lead and zinc. If all the metal is in dissolved form (i.e. no particulate metal), then the dissolved concentration should equal the total concentration. When particulate metals are present, total concentrations are greater than dissolved, and the proportion of particulate metal can be estimated from the ratio of total to dissolved concentrations. For example, if the total concentration is twice the dissolved concentration, then 50% of the metal is in particulate form. The plots show that the proportion of particulate metals is variable but more than 50 percent of the cadmium and up to 90 percent or more of the copper, lead, and zinc in the river water can be present in particulate form. This highlights the importance of metals partitioning to and transport with suspended particles near the location on the Columbia River at which the metals load enters the UCR Site. This is based on analysis of recent water quality data, while metal loads and, thus, suspended metal loads from historic discharges would have been much greater.

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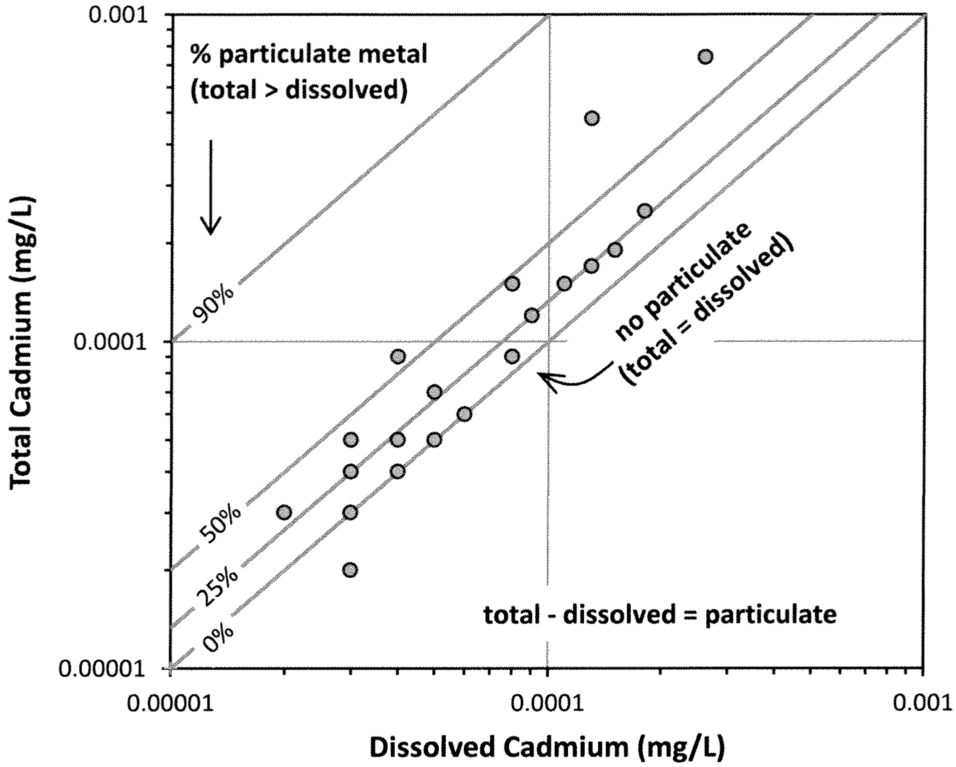

Figure 6. Total and dissolved cadmium concentrations in the Columbia River at Waneta and estimated percentage particulate fraction

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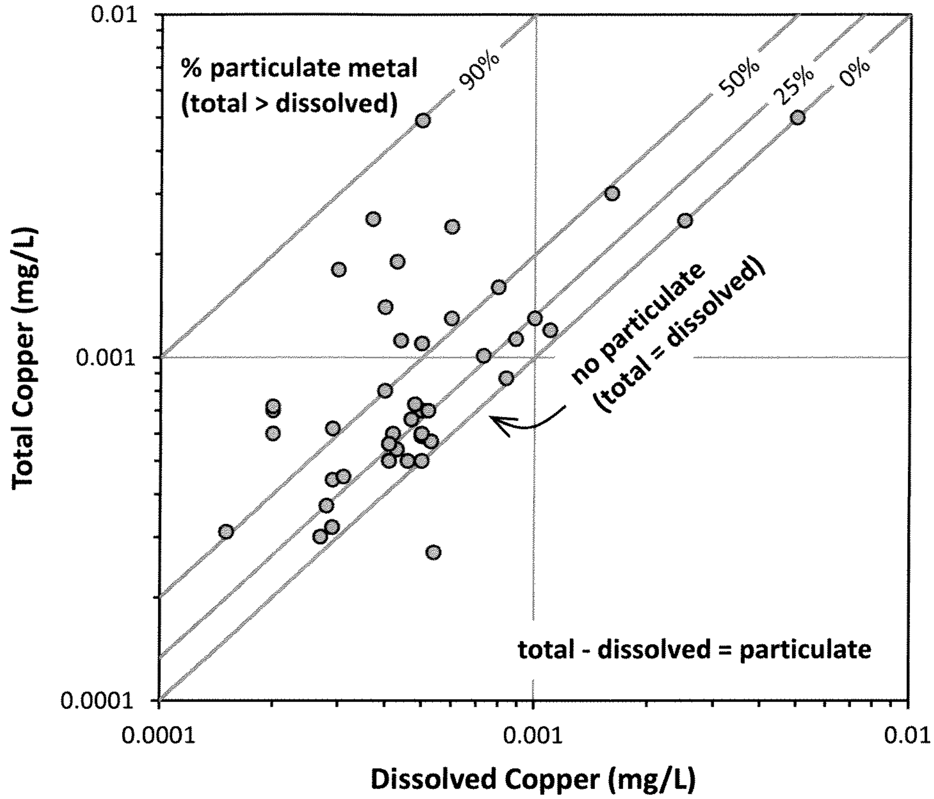

Figure 7. Total and dissolved copper concentrations in the Columbia River at Waneta and estimated percentage particulate fraction

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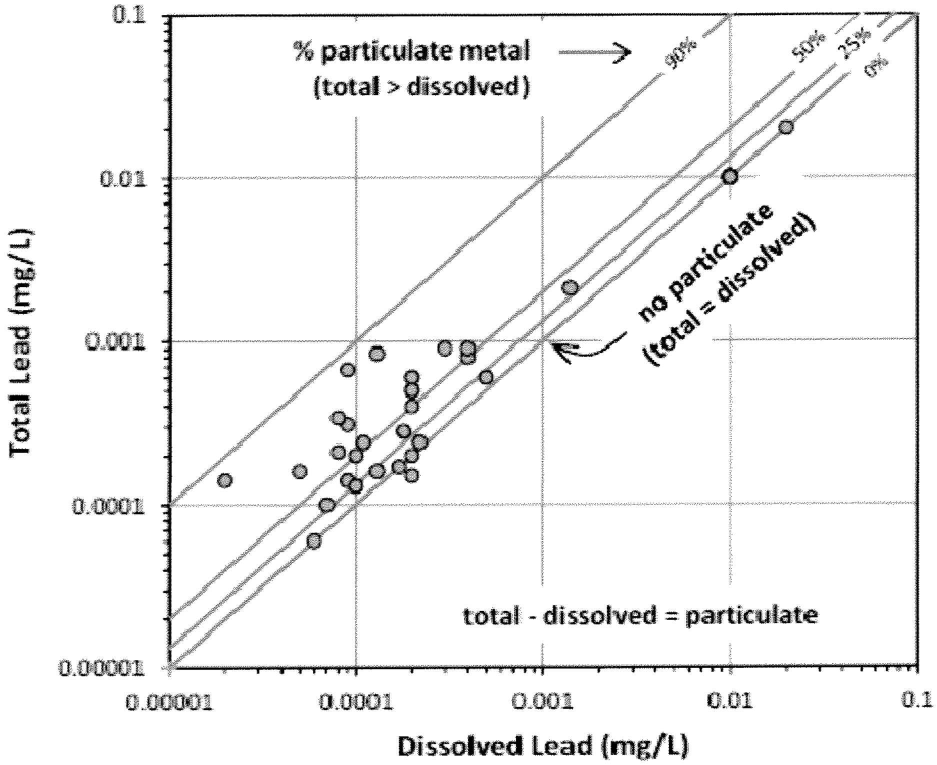

Figure 8. Total and dissolved lead concentrations in the Columbia River at Waneta and estimated percentage particulate fraction

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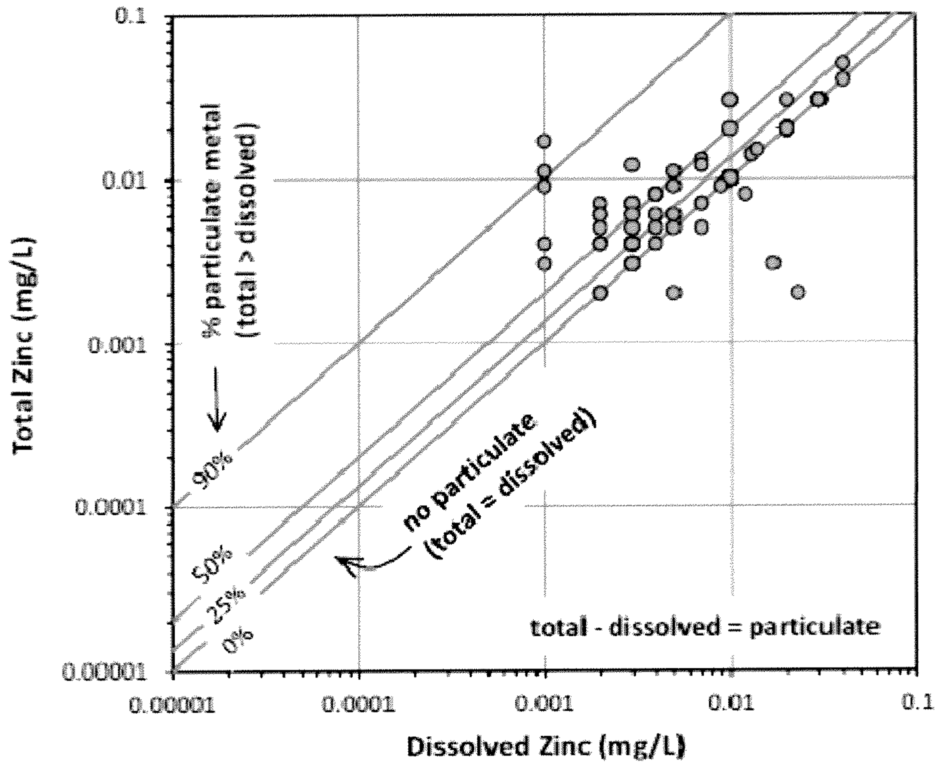

Figure 9. Total and dissolved zinc concentrations in the Columbia River at Waneta and estimated percentage particulate fraction

(2) The Columbia River has the capacity to both transport and deposit all forms of Teck's sewer effluents to the UCR Site.

50. While dissolved metals are transported with flowing water until they sorb onto particulate matter in the surface water or on the river bed, suspended particles are subject to sedimentation. Larger, denser particles and grains will settle out before finer, less dense particles. Depending on variables such as grain size and density, coarser particulate matter will settle out of the water quickly and be transported primarily along the river bed at a rate slower than the water; whereas, metals associated with finer suspended particles will be carried further downstream before being deposited.

51. Applying these principles to sediment inputs—including Teck sewer

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